UNCLASSIFIED

AD NUMBER
AD833880
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited.**
FROM: **Distribution authorized to U.S. Gov't. agencies and their contractors; Critical Technology; MAR 1968. Other requests shall be referred to Army Electronics Command, Attn: AMSEL-KL-TM, Fort Monmouth, NJ. This document contains export-controlled technical data.**
AUTHORITY
usaec ltr, 27 jul 1971

THIS PAGE IS UNCLASSIFIED

AD

SU-IPR Report No. 231

AD833880

RESEARCH AND DEVELOPMENT
TECHNICAL REPORT ECOM-02041-12

Investigation of Fast Wave Beam/Plasma Interactions

Quarterly Report No. 8

March 1968

This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of CG, USAECOM, Attn: AMSEL-KL-TM, Ft. Monmouth, N.J.

Sponsored by
Advanced Research Projects Agency Project Defender
ARPA Order No. 695

ECOM

UNITED STATES ARMY ELECTRONICS COMMAND · FORT MONMOUTH, N.J.
CONTRACT DA-28-043-AMC-02041(E)

INSTITUTE FOR PLASMA RESEARCH
STANFORD UNIVERSITY, STANFORD, CALIFORNIA

38

NOTICES

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

The citation of trade names and names of manufacturers in this report is not to be construed as official Government indorsement or approval of commercial products or services referenced herein.

Destroy this report when it is no longer needed. Do not return to the originator.

Technical Report ECOM-02041-12

Reports Control Symbol
OSD-1366

INVESTIGATION OF FAST WAVE BEAM/PLASMA INTERACTIONS

U. S. Army Electronics Command
Fort Monmouth, New Jersey

REPORT NO. 12

CONTRACT DA-28-043-AMC 0204.(E)

8th QUARTERLY REPORT

1 December 1967 - 29 February 1968

SU-IPR Report No. 231
March 1968

Institute for Plasma Research
Stanford University
Stanford, California

BLANK PAGE

PERSONNEL

Contract DA-28-043 AMC-02041(E)
for the period
1 December 1967 - 29 February 1968

Senior Staff

F. W. Crawford, part time
(Principal Investigator)

T. J. Fessenden, part time

J. R. Forrest, part time

S. A. Self, part time

Part Time Graduate Research Assistants

P. L. Anderson

J. C. Lee

V. Ristic

T. D. Rognlien

ABSTRACT

This report describes a program of work on beam/plasma interaction. Both electrostatic and electromagnetic wave amplifying mechanisms are under investigation. For the former, studies in the absence of a static magnetic field are directed towards verifying the theory for beam/surface wave amplification. Two distictly different lines are being followed for interactions in the presence of a static magnetic field: Electrostatic cyclotron harmonic wave interaction is being examined, both theoretically and experimentally, and the potentialities of electromagnetic wave growth in the "whistler" mode are being investigated.

FOREWORD

This contract represents a three-year program of research on "Fast Wave Beam/Plasma Interactions" which is proceeding in the Institute for Plasma Research, Stanford University, under the direction of Prof. F. W. Crawford as Principal Investigator. The work is part of PROJECT DEFENDER and was made possible by the support of the Advanced Research Projects Agency under Order No. 695. It is conducted under the technical guidance of the U. S. Army Electronics Command. This is the eighth Quarterly Report, and covers the period 1 December 1967 to 29 February 1968.

CONTENTS

LIST OF FIGURES

I. INTRODUCTION

The wave amplification effect associated with the interaction of an electron beam and a plasma has attracted considerable attention over the last few years, particularly from microwave tube specialists to whom such interactions offer possibilities of constructing very high gain devices which should be electronically tunable over wide frequency ranges. Since the plasma plays the role of a conventional slow-wave structure, the interaction region should be free of metallic structures, a particularly significant characteristic if millimeter wave operation is envisaged.

The work being carried out under this contract is directed towards utilizing the beam/plasma amplification mechanism in microwave device applications. So far, despite the efforts of many groups, it has not been possible to realize this potential fully. The most serious obstacles to progress are that efficient coupling of an rf signal into and out of the interaction region has been found difficult to achieve, and that the amplifiers are frequently very noisy compared with most conventional microwave tubes. The necessity of providing the means of plasma generation within the device, and the presence of a relatively high background gas pressure, add constructional problems beyond those normally encountered with vacuum tubes. Although satisfactory engineering solutions to these latter difficulties could certainly be found, the coupling and noise problems still require considerable further study to determine whether competitive devices can be developed.

Of the many widely differing aspects of beam/plasma interaction, three have been chosen for close examination under this contract. The first of these is the interaction of an electron beam with a plasma when the modulating fields, and the wave growth, are in either the first axisymmetric mode, or in the first azimuthally-varying mode. Since with transverse modulation several interesting interaction and coupling mechanisms become possible, it is intended that a thorough investigation of such phenomena should be made under this contract.

Most previous work has been concerned with the theoretical description and demonstration of beam/plasma interaction mechanisms that can be derived from cold plasma theory, i.e., from theory in which it is assumed that the plasma electrons have no thermal or directed motions, and that the injected beam is monoenergetic. When a dc magnetic field is present, microscopic theory, in which single-particle behavior is followed, predicts a much wider range of amplification mechanisms. Some of these are simply modifications of those occurring in the absence of the magnetic field, while others involve interaction of beams with transverse energy with slow "cyclotron harmonic waves." This constitutes our second area of interest, i.e., that of wave growth in magnetoplasmas when the electron beam has a substantial component of transverse energy.

Our third area of interest is in electromagnetic wave amplification. Theoretical studies show that, in addition to electrostatic wave growth phenomena such as those just described, there is the possibility of obtaining appreciable growth in the "whistler" mode when an electron beam with transverse energy interacts with a magnetoplasma. This mode is a right-hand, circularly-polarized electromagnetic wave, i.e., its electric field vector rotates in the right-hand sense, which is also (conventionally) the sense of rotation of the electrons about the magnetic field lines. If a beam with transverse energy is moving along the field lines, there is consequently a possibility of energy being transferred from the electrons to the wave, and hence, for wave amplification to occur. The purpose of our work is to demonstrate this type of interaction, and to examine its potentiality for coupling to slow- and fast-wave circuits. Here "fast-wave" is interpreted to mean that the phase velocity of the wave is of the order of the velocity of light.

Previous quarterly reports (QR) have described the background for each of the topics in detail. Progress made during the reporting period will be described in the succeeding sections.

II. BEAM/PLASMA AMPLIFICATION

Amplification due to interaction of an electron beam with an unmagnetized plasma has been studied at Stanford and elsewhere. Experimentally, electronic gains as high as 20 dB/cm have been observed in both $m = 0$ and $m = 1$ modes, at frequencies up to 1 GHz, and reasonable agreement has been obtained with theoretical predictions. Although electronic gain has been observed, however, the achievement of net gain between an input and an output is an elusive goal due to the difficulty of achieving efficient coupling between the beam/plasma system and external circuits. One of the principal aims of this study is to investigate coupling methods in the hope of realizing net gain.

When the beam fills, or nearly fills, the plasma region, the rf fields penetrate appreciably into the region external to the plasma. Under these conditions, and provided that the plasma is bounded by a dielectric (with or without an additional external conductor), the interaction is effectively between the space-charge waves of the beam and surface waves propagating on the plasma column. In this case, it should be possible to couple efficiently to circuits external to the plasma. For this reason we are studying, both theoretically and experimentally, as reported in Sections A and B below, a system in which the beam and plasma fill a dielectric tube.

During the past quarter, further computations of the surface wave dispersion relation relevant to the experimental tube have been carried out. Some useful analytic approximations have been derived in order to check the numerical computations. Experimental work on beam/plasma interaction has been carried out with a sealed-off tube containing mercury-vapor, in order to clarify further the experimental results presented in QR 5 and 6, and with a new cold cathode tube connected to a continuously pumped system filled with helium.

(A) Theoretical Studies

Previous QR's have described theory and computations for the $m = 0$ and $m = 1$ dispersion relations. Also, some stability considerations have been presented for the asymmetric (m=0) mode. Following these lines, it has been established that the second order approximation for the function $F_m(z)$, defined in QR 6, is adequate to represent the m=0 and m=1 modes. In this approximation, both modes have finite gain at the plasma frequency. The search procedure used in the computer to calculate the exact dispersion relation has been modified since the preliminary computations for the m=1 mode described in QR 7 suggested infinite gain at the reduced plasma frequency. With an improved numerical procedure, it is now found that the gain is finite and that the analytical and numerical results agree. Some preliminary investigation of the system stability has been carried out. This indicates that for our experimental parameters, both m=0 and m=1 modes should be absolutely unstable, through collisions and nonzero electron temperature.

The experimental results presented in previous QR's indicate that there may be a strong density gradient along the discharge axis. This might be taken into account by the well known WKB approach. An alternative technique from the theory of nonlinear systems has been studied during the reporting period. Some work has already been carried out using this approach for the case of an infinite warm plasma with a slowly varying density along the axis.[1,2] This line will be pursued during the coming quarter, particularly with a view to determining how the beam/plasma interaction synchronism condition, and resulting gain, are affected.

(B) Experimental Studies

During the quarter, the new cold-cathode experimental tube described in QR 7 was set up on a continuously pumped system, and exploratory measurements were made with helium as the working gas. It will be recalled that the reasons for using this type of discharge were, first, to avoid the use of oxide cathodes, and, second, to obtain directly a large diameter electron beam. It was found immediately that the conditions described elsewhere for cold cathode discharges in helium[3] were not reproduced in our experimental situation. Over 6 kV were required to start the tube at p = 0.5 mTorr. At higher pressures, pronounced striations were observed along the tube. No improvement could be obtained by applying an axial magnetic field. We have concluded that the difference between our results and those of Persson[3] is due to the very much smaller diameter of our experimental tube. It was decided to abandon the method and to use an electron gun of the type described in earlier reports on sealed-off tubes. Such a gun is under construction and should be available shortly for use on the continously pumped system.

While waiting for the new tube, some further experiments have been carried out on the sealed-off mercury-vapor discharge tube in the region of propagation where there is no appreciable electronic gain. The measurements were carried out to provide more data on the longitudinal profile of the plasma column. The data given in Figs. 1 and 2 were taken at three different frequencies, for two different values of the beam voltage. It will be seen that the wavelength of the space envelope changes with distance in a nonperiodic way. Such behavior has been exhibited previously in QR 6 and may owe its origin to four possible basic mechanisms: (i) beating of a single propagating mode with a direct signal coupled internally through the tube, or from outside, (ii) beating, or standing waves, due to partial reflection of a single mode from the end of the system, (iii) beating of two waves propagating in the same direction, and (iv) inhomogeneity along the axis. Further experiments are under way to determine which of these is appropriate to our experimental results.

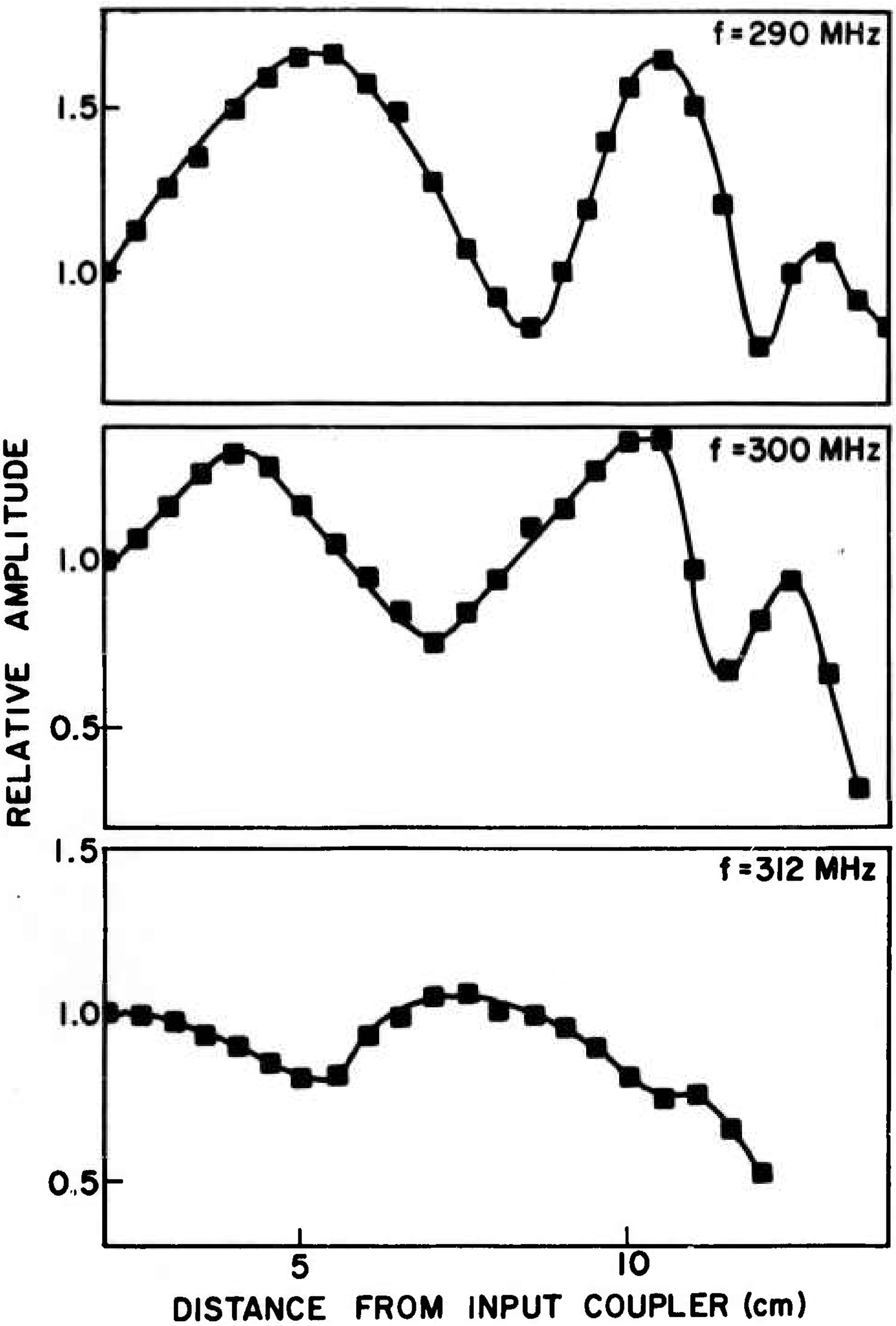


Fig. 1. Amplitude variation with distance along tube for various applied signal frequencies (V_b = 100 V, I_c = 1.0 mA).

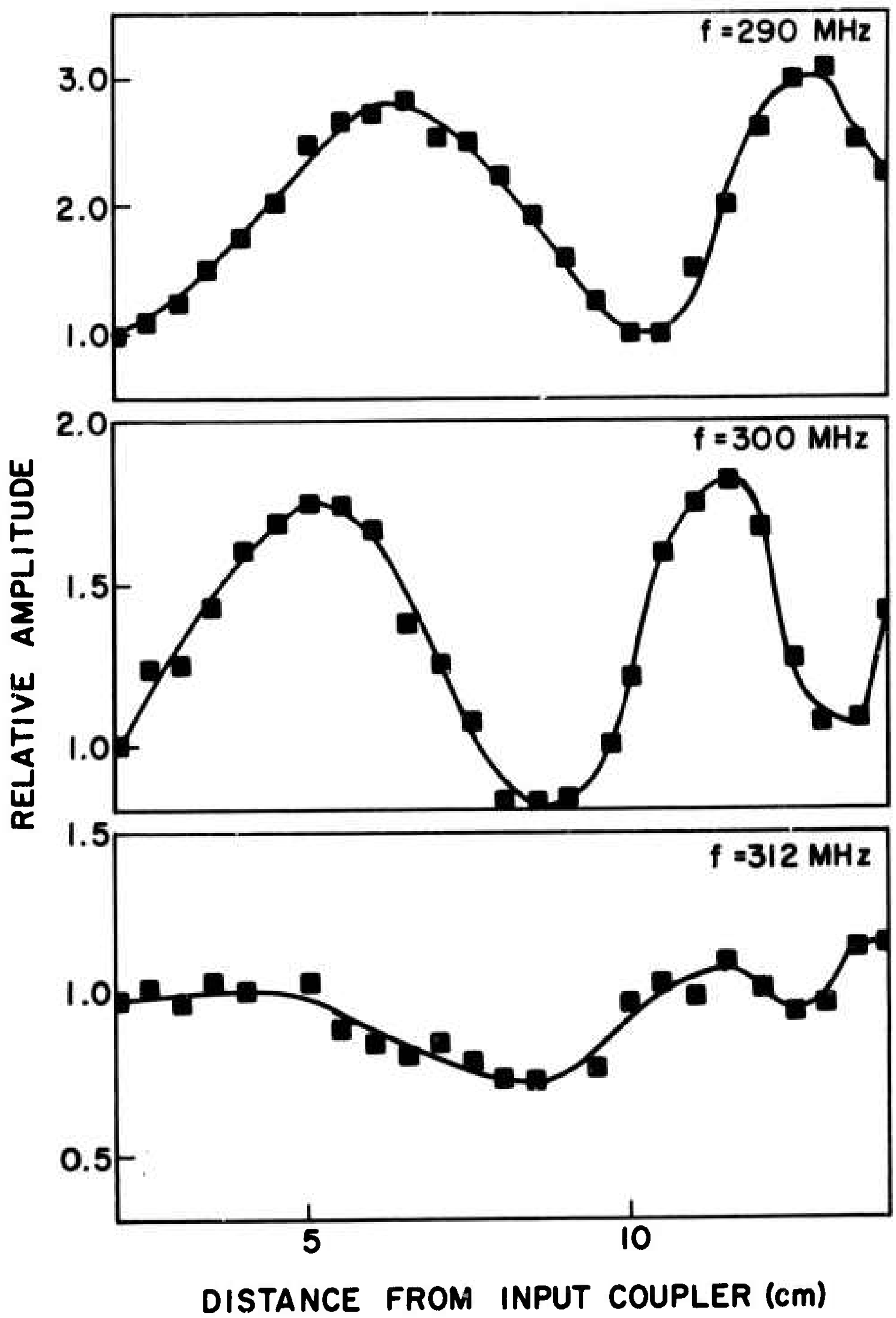


Fig. 2. Amplitude variation with distance along tube for various applied signal frequencies (V_b = 100 V, I_c = 0.8 mA).

III. ELECTROSTATIC WAVE AMPLIFICATION IN MAGNETOPLASMAS

When the beam and/or plasma have directed or thermal motions in the transverse and axial directions, it is necessary to derive the appropriate dispersion relations using a Boltzmann equation formalism. The results of doing so were discussed rather generally in QR 1 where it was pointed out that, for a high enough value of the parameter (ω_b/ω_c), i.e., the ratio of beam plasma frequency to electron cyclotron frequency, even an ion-neutralized electron beam could be unstable, and that in the presence of a background plasma the instability threshold for the beam density could be reduced. The purpose of this project is to investigate such interactions, and to determine their potentialities for microwave applications.

Numerous theoretical predictions of the instabilities have been made at Stanford and elsewhere. Basically, the theory predicts growth in passbands centered on the electron cyclotron harmonic frequencies $(n\omega_c)$. No further computations will be carried out under this project until our experimental parameters have been measured. Those computations carried out to date have been summarized in a Ph.D. thesis by Tataronis[4].

So far, few controlled experiments have been carried out to check the theory, though observations of strong noise emissions from magnetoplasmas containing charged particles with appreciable transverse velocities provide significant support for the existence of the predicted mechanisms. The studies planned under this contract are intended to provide results under refined experimental conditions, and to put the theory on a firm quantitative basis. In particular, we wish to verify the dispersion relation for the realistic case of a delta-function beam interacting with a warm plasma. The aim is to excite growing waves by means of an electron beam injected into the plasma, and to study the variation of the growth rate as a function of the longitudinal and transverse energies of the beam. This immediately poses two experimental problems: production of the beam, and measurement of its parameters. These topics will be discussed in Section III A. Some experimental results on instabilities excited by the beam are presented in Section III B.

(A) Electron Beam Production and Measurement

One way of imparting transverse energy to a beam is to inject it through an increasing magnetic field into the interaction region. This does not create the delta-function transverse velocity distribution which would be most desirable for checking against theory. A closer approach to this is the use of a "corkscrew" injection system.[5] A third method which we hoped to apply, because of its greater flexibility, is to impart transverse energy to the electrons by cyclotron heating in a small rf cavity through which the beam passes before entering the plasma region. This has been found extremely difficult to realize for our experimental conditions, however. For convenience in our initial studies, a version of the first method has been adopted, and was described in detail in QR 7. Briefly, it consists of a large oxide-coated cathode oriented at an angle to the magnetic field. Grids are used to vary the energy picked up by the electrons emitted from the cathode before their injection into the main discharge region. A pair of Helmholz coils allows the magnetic field at the cathode surface to be varied independent of the main field.

The operation of the electron injection scheme has been investigated during the reporting period. A series of experiments were performed on the beam produced by the angled cathode structure. Measurements were made at the anode of the system, approximately 60cm from the cathode. During these experiments, the neutral pressure was kept as low as possible [$< 10^{-4}$ Torr] to avoid producing a plasma. The gridded probe device mentioned in QR 7 was completed and used to measure the parallel velocity of the beam at the position of the anode. Figure 3 shows typical experimental data obtained from the analyzer with the aid of an operational amplifier and an oscilloscope.

The perpendicular velocity distribution function, $F(v_\perp)$, can be inferred from the parallel velocity distribution function given by Fig. 3. We have

$$F(v_\perp) = f(V_b - V_\perp) \quad , \tag{1}$$

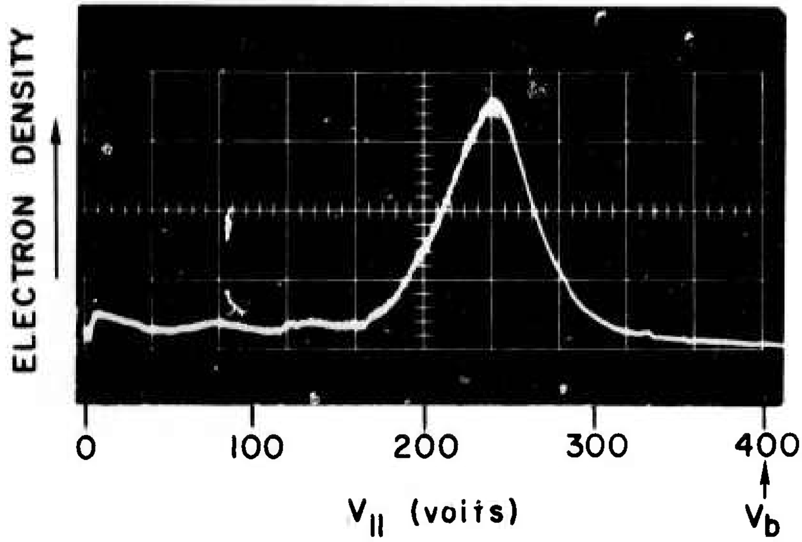


Fig. 3. Parallel electron velocity distribution function obtained by use of the velocity analyzer.

if there is no plasma. This follows directly, because all electrons are assumed to have the same total energy, eV_b. Thus

$$V_\perp + V_\parallel = V_b . \qquad (2)$$

The analyzer was used to make two different experimental checks. First, the adiabatic theory was checked qualitatively, and the maximum percentage of beam energy that could be injected perpendicular to the magnetic field was measured. Figure 4 shows the percentage of the beam energy in the transverse motion of the particles, as a function of magnet current in the main coils, for various beam voltages. In taking these data, the magnetic field at the angled cathode was kept constant. The fact that these data fall on a straight line intersecting the origin is a qualitative check on the adiabatic theory.

That the slopes of the curves presented in Fig. 4 depend on the beam voltage is a property of the angled cathode. If the magnetic field at the cathode is very weak, and the accelerating voltage, V_b, is large, electrons emitted from the cathode follow nearly straight line paths. The energy parallel to the field, $V_\parallel$, is then given by

$$V_\parallel = V_b \sin^2\theta , \qquad (3)$$

while their perpendicular energy is given by

$$V_\perp = V_b \cos^2\theta , \qquad (4)$$

where θ is the angle the cathode makes with the magnetic field. If the magnetic field is strong, the electrons are constrained to follow the field lines, and all the energy appears as parallel energy. The important parameter is the ratio, R, of the grid-to-cathode spacing, d, to the Larmor radius, λ_r .

Figure 5 is a plot of the percentage energy in the transverse motion as a function of R. The solid line is a theoretical result

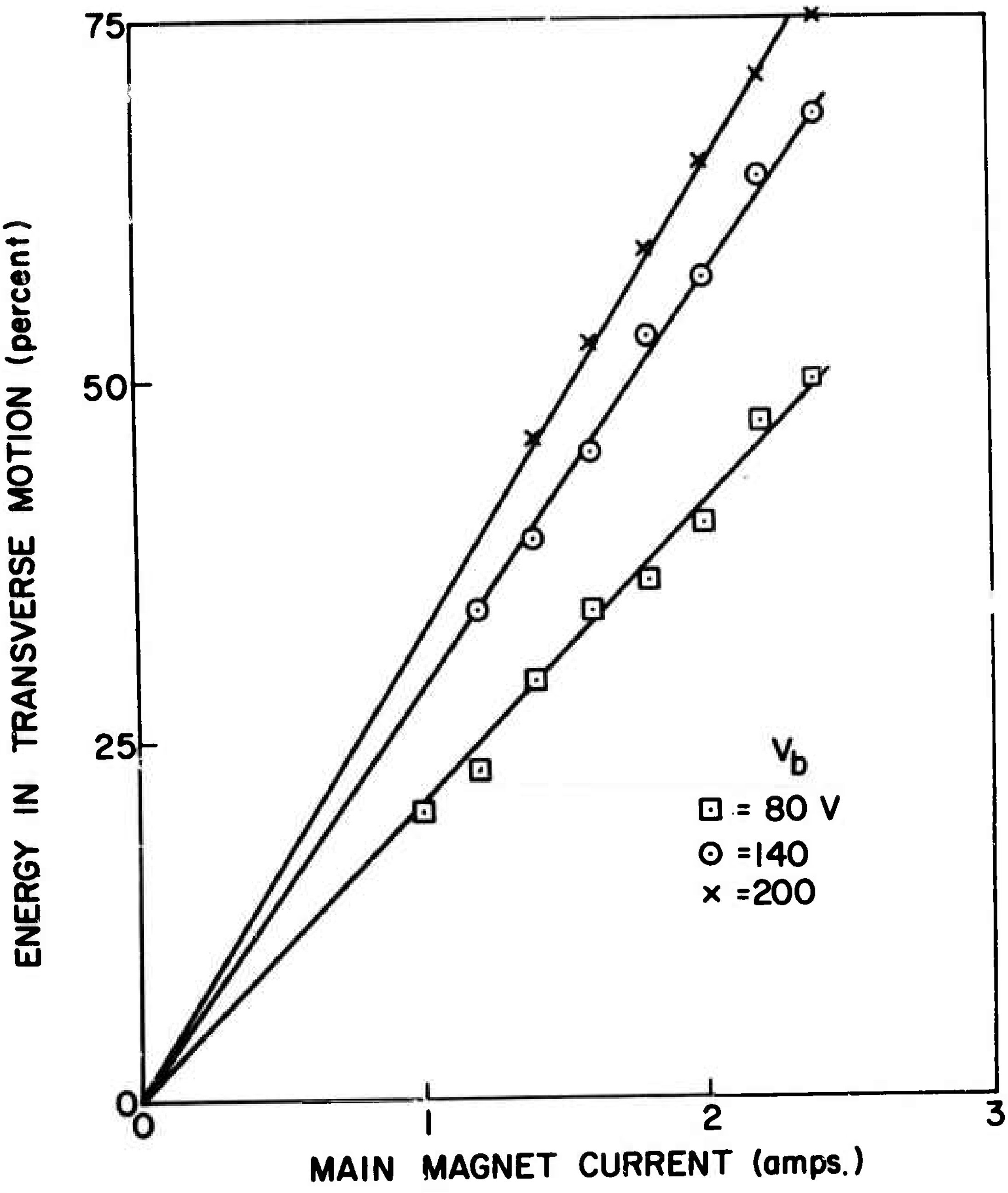


Fig. 4. Percentage energy in transverse motion of the electron beam as a function of magnetic field at the analyzer (magnetic field at the cathode was held constant at 100 gauss.

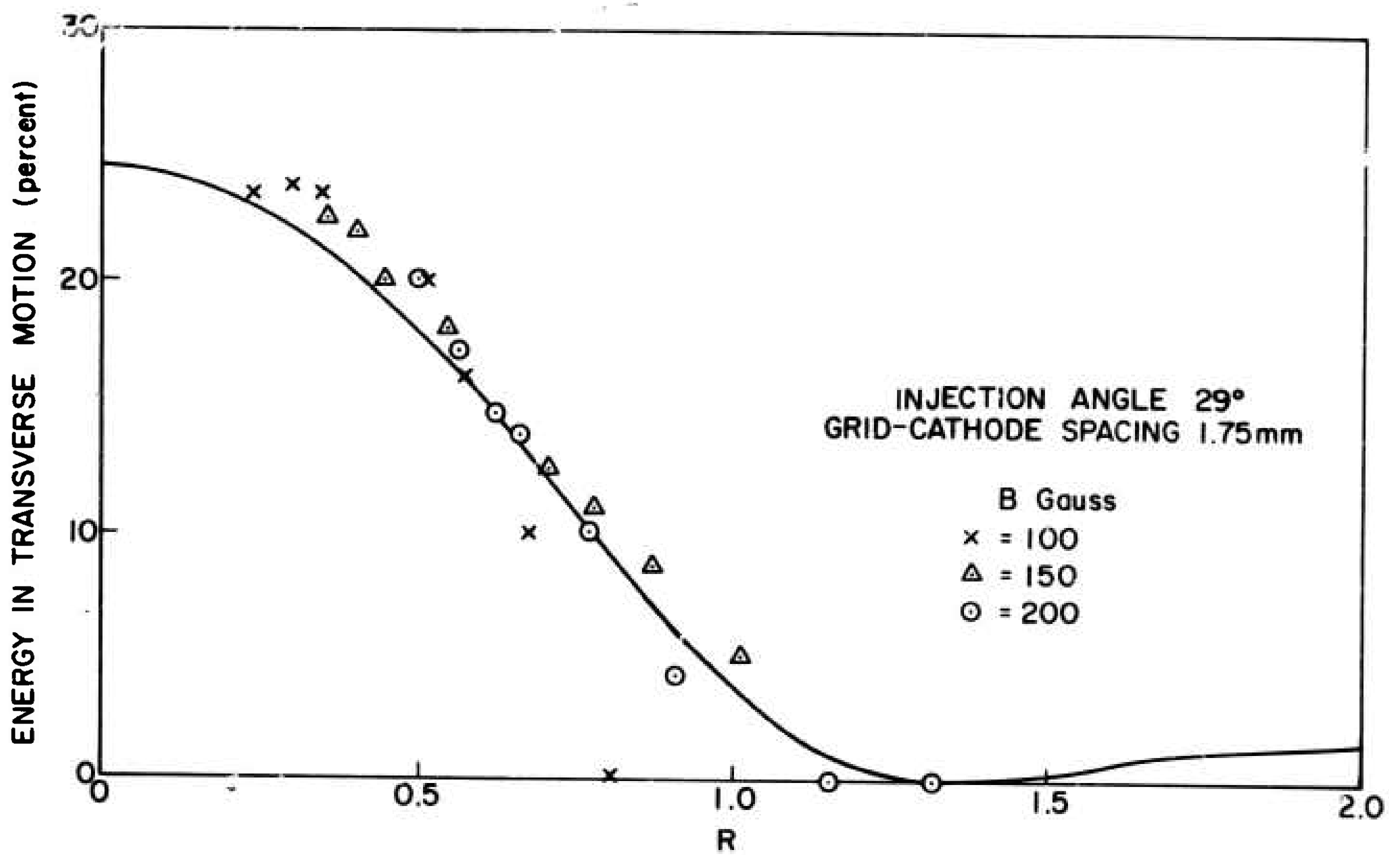


Fig. 5. Theoretical and experimental plot of the percentage transverse energy of the electron beam at the accelerating grid as a function of $R(\equiv d/\lambda_r)$.

obtained by solving for the electron trajectories in the grid-to-cathode region. The points were obtained by use of the gridded probe, as the beam voltage was varied at each of the three magnetic fields indicated.

(B) Observations of Emissions from the Plasma

The theory of cyclotron harmonic wave instabilities seems to indicate absolute, rather than convective, growth under most experimental conditions, and most experiments in this area have concerned plasma noise emissions at or near the cyclotron harmonics. During the reporting period, we have continued our studies of plasma noise emissions stimulated by the electron beam having transverse energy described in Section III A. Among the prominent peaks in the frequency spectrum is one at the electron cyclotron frequency scaling linearly with magnetic field. This characteristic is illustrated in Fig. 6.

The radiation at the fundamental cyclotron frequency is accompanied by peaks at the harmonics. A phenomenon observed to be associated with these is that, as the plasma density decreases, the odd cyclotron harmonics disappear, leaving only the even harmonics. This point is demonstrated in Fig. 7 where emission spectra are compared for two values of plasma density. Further observations are that the spectral lines broaden with increasing plasma density, and that radiation spectra, similar in shape but 10-20dB weaker in amplitude, can be picked up outside the discharge tube by means of a monopole antenna. Further experiments are under way to elucidate the nature of the resonances and to account for the differing behavior of even and odd harmonics of the cyclotron frequency.

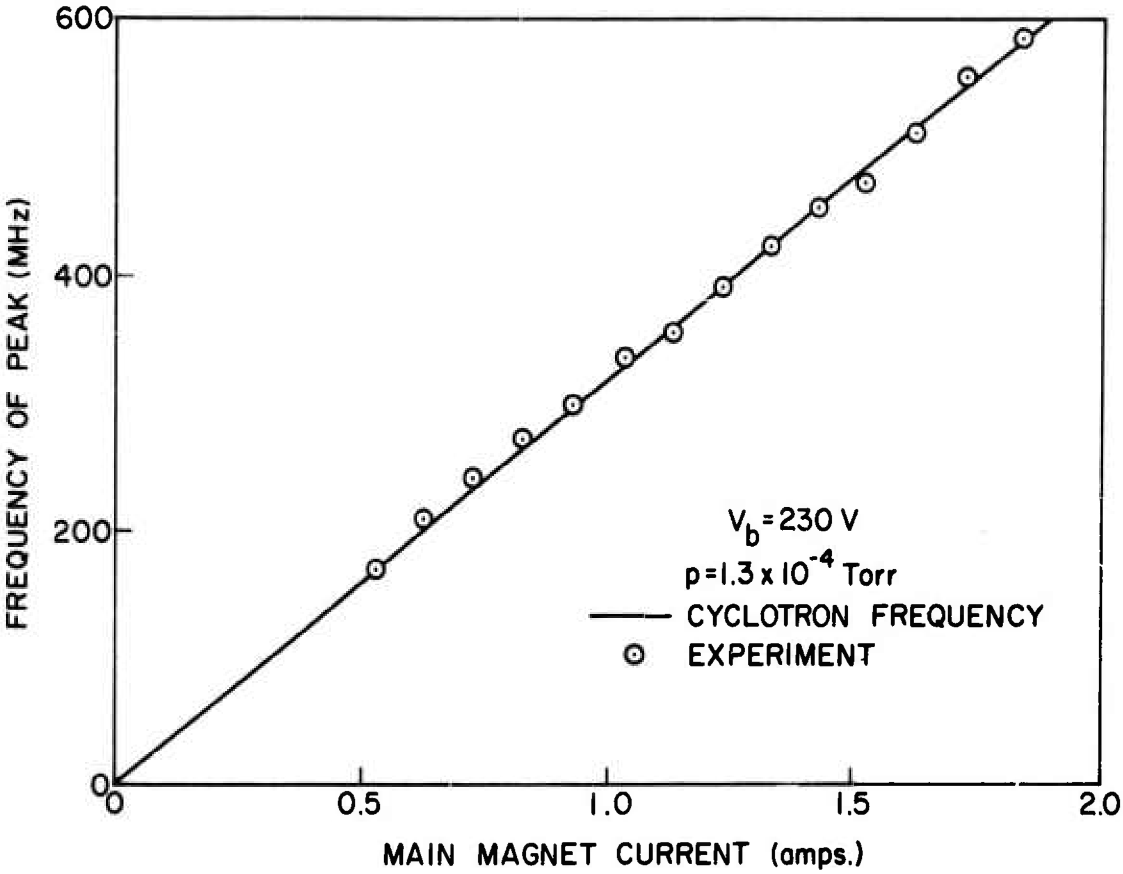


Fig. 6. Noise emission from a magnetoplasma: Cyclotron frequency radiation.

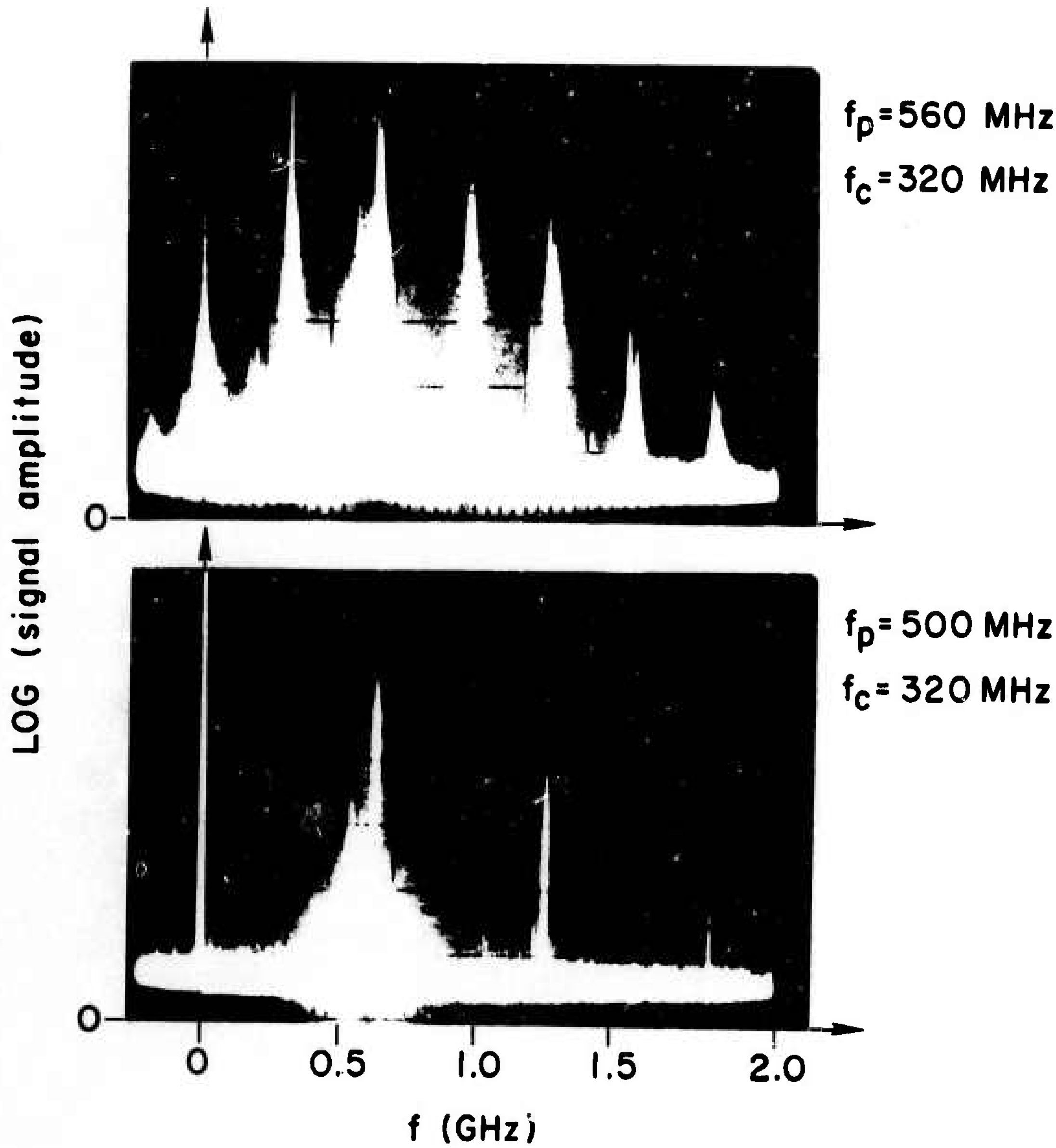


Fig. 7. Noise emission from a magnetoplasma: Cyclotron harmonic radiation.

IV. ELECTROMAGNETIC WAVE AMPLIFICATION IN MAGNETOPLASMAS

In the absence of a static magnetic field, interaction of an electron beam with a plasma leads only to electrostatic beam/plasma interactions of the types described in Section II. When a static magnetic field is present, there are additional possibilities of electromagnetic wave interaction. That of special importance under the present contract is the interaction with the right-hand polarized electromagnetic wave known in ionosphere terminology as the "whistler" mode. It has been demonstrated theoretically that under conditions where a beam with transverse energy interacts with the plasma, wave growth in this mode should be possible. This leads immediately to the question of whether there are experimental situations in which this growth dominates over the electrostatic growth mechanisms occurring at the same time. Some previous studies suggest that such conditions are realizable, but are not conclusive. Examination of this question is one of the major topics of interest under the project.

Comparatively little experimental work has been reported so far on propagation of the whistler mode in laboratory plasmas, and none of this seems to have been directed towards observation of wave growth due to interaction with a gyrating electron stream, or to other wave amplifying mechanisms such as parametric amplification. Such demonstrations form the primary object of this project. If growth in the whistler mode could be demonstrated, and utilized, it would offer very attractive practical features. In particular, coupling should be facilitated, since the amplification occurs in an electromagnetic mode, i.e., without conversion to an electrostatic mode.

The aims of the present project are as follows: First, to elucidate the theory of whistler-type instabilities in the simplest geometry, and then to extend this to more realistic physical conditions, and second to demonstrate directly by experiment that growth can occur in this mode.

(A) Theoretical Studies

Previous QR's have dealt with the question of wave growth in the whistler mode due to interaction with an electron beam having transverse energy. A large number of computations have now been carried out, taking a wide variety of experimental parameters into account. The work is being written up in report form, and will be available shortly, so that it is only necessary to summarize briefly here the salient features of our numerical work. For a monoenergetic beam, in which all particles have the same transverse speed as they gyrate about the magnetic field lines, weak absolute instabilities are predicted. These can be stabilized, by collisions or nonzero electron temperature in the background plasma, to leave a convective instability which might be useful in a microwave amplifier.

In addition to the growth in the whistler mode, there are two competing instabilities: growth of cyclotron harmonic waves by the electrostatic mechanism of interest in Section III, and beam/plasma interaction. The first of these can occur due to the transverse energy alone of the beam. The second requires only the existence of longitudinal energy. Our computations suggest that experimental conditions can easily be obtained in which the cyclotron harmonic wave instabilities are of negligible importance, but that the conditions for whistler growth due to a beam will always lead to strong longitudinal beam/plasma interaction.

An objection that can be raised to these results is that they have been obtained from dispersion relations. Computations of growth rates from linear theory provide no indications whatsoever of the amplitudes to which the competing instabilities may grow. To decide this issue would require full nonlinear treatments of the wave growth in the whistler mode, and in competing modes, to determine whether the slower-growing whistler mode would ultimately reach the highest amplitude. Such an analysis is probably prohibitively complicated for an experimental situation.

Three alternatives remain. The first is to explore other velocity distributions to determine whether conditions exist for which growth in the whistler mode predominates over other types of instabilities. There is some evidence, from observation of whistler amplification in the magnetosphere, that such conditions exist. A second is to determine by experiment which mode reaches the highest amplitude. This is unattractive to us since the possibility of making fundamental comparisons with theory would be lost, and in any case, this is not a satisfactory basis for design or operation of a practical amplifier. The third possibility is to examine mechanisms for whistler amplification in which the energy source to provide wave growth is not supplied in the form of an electron beam.

In our future work, attention will be paid to the first and third possibilities suggested in the last paragraph. In particular, the loss-cone distribution will be studied, since it can easily be produced in a magnetic mirror, and it is involved in whistler growth in the magnetosphere. For interactions leading to wave growth by other than velocity-space mechanisms, parametric amplification represents an extremely interesting possibility. Plasma is known to be strongly nonlinear, and it may be possible to utilize this property in a whistler mode parametric amplifier.

Some preliminary work on this last topic has been carried out during the reporting period. The aim has been to determine whether the synchronism conditions between the signal, idler and pump frequencies (ω_s, ω_i and ω_p) and wave-numbers (k_s, k_i and k_p) can easily be satisfied by the whistler mode dispersion relation. This can very readily be shown to be the case by considering, as an example, the conditions to be satisfied for a degenerate parametric amplifier ($\omega_s = \omega_i$, $k_s = k_i$). We require

$$\omega_p = 2\omega_s = 2\omega_i \quad , \quad k_p = 2k_s = 2k_i \quad , \tag{5}$$

to satisfy the whistler dispersion relation,

$$\frac{k^2c^2}{\omega^2} = 1 - \frac{\omega_p^2}{\omega(\omega-\omega_c)} \quad . \tag{6}$$

It is easily seen that this leads to,

$$\omega_p = \frac{2\omega_c}{2} \quad , \quad \omega_i = \omega_s = \frac{\omega_c}{3} \quad , \tag{7}$$

independent of the electron density. All of these frequencies are well separated from the regions of the dispersion curve where cyclotron and collision damping are important. During the coming quarter, the full nonlinear theory will be derived to obtain the growth parameter for the interaction.

(B) Experimental Studies

Our main experimental effort during the reporting period has been to extend the whistler propagation measurements begun last quarter in the large (K-band) magnetic field system. The preliminary data described in earlier QR's have been supplemented by measurements close to the cyclotron frequency, where collisionless damping is to be expected. This is a fundamental measurement which has not been made in precise detail in any previous laboratory work on whistlers. Our aim is to obtain both the real and the imaginary parts of the whistler dispersion relation for comparison with theory.

When reflections from the ends are minimized in the system, typical interferograms and transmission curves are as shown in Fig. 8, for which the experimental conditions were as follows. The maximum ion saturation current taken during the current pulse by a Langmuir probe located 1.13 cm from the column edge was 15 mA. At a sampling time 700 μs after the pulse, the ion saturation current was 0.8 mA corresponding to a plasma frequency of 11.5 GHz. The magnetic field corresponding to a coil current of 55 A was such as to provide a cyclotron frequency of 2 GHz. The argon pressure was 7 mTorr. Whistlers were observed at signal frequencies of 2.0, 1.9, 1.8, and 1.7 GHz, and the resulting dispersion curve is given in Fig. 9. The measured complex whistler dispersion is compared in this figure with the theoretical complex dispersoon curve for $(\omega_p/\omega_c)^2 = 20$, electron temperature $T_e = 3$ eV, and collision frequency $\nu = 0.01\ \omega_c$. The damping measurement seems to suggest that the actual magnetic field is slightly higher than calculated from wavelength measurements. The 25.2 GHz interferometer calibration of the electron plasma frequency against ion saturation current seems to be lower than the value suggested by the whistler measurements.

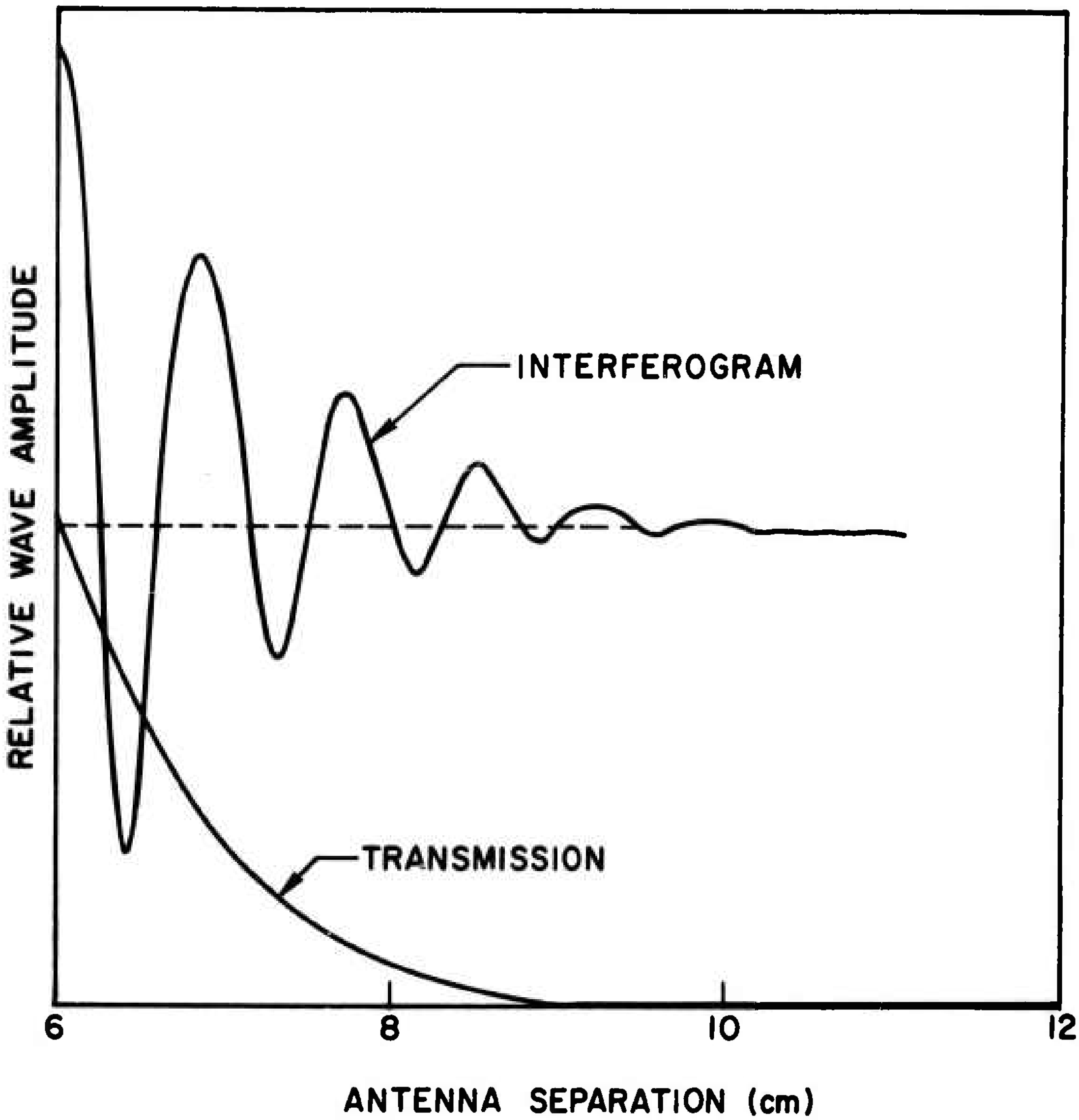


Fig. 8. Whistler dispersion characteristics: Interferogram and transmission records ($f = 1.9$ GHz, $f_c = 2.0$ GHz, $f_p = 11.5$ GHz).

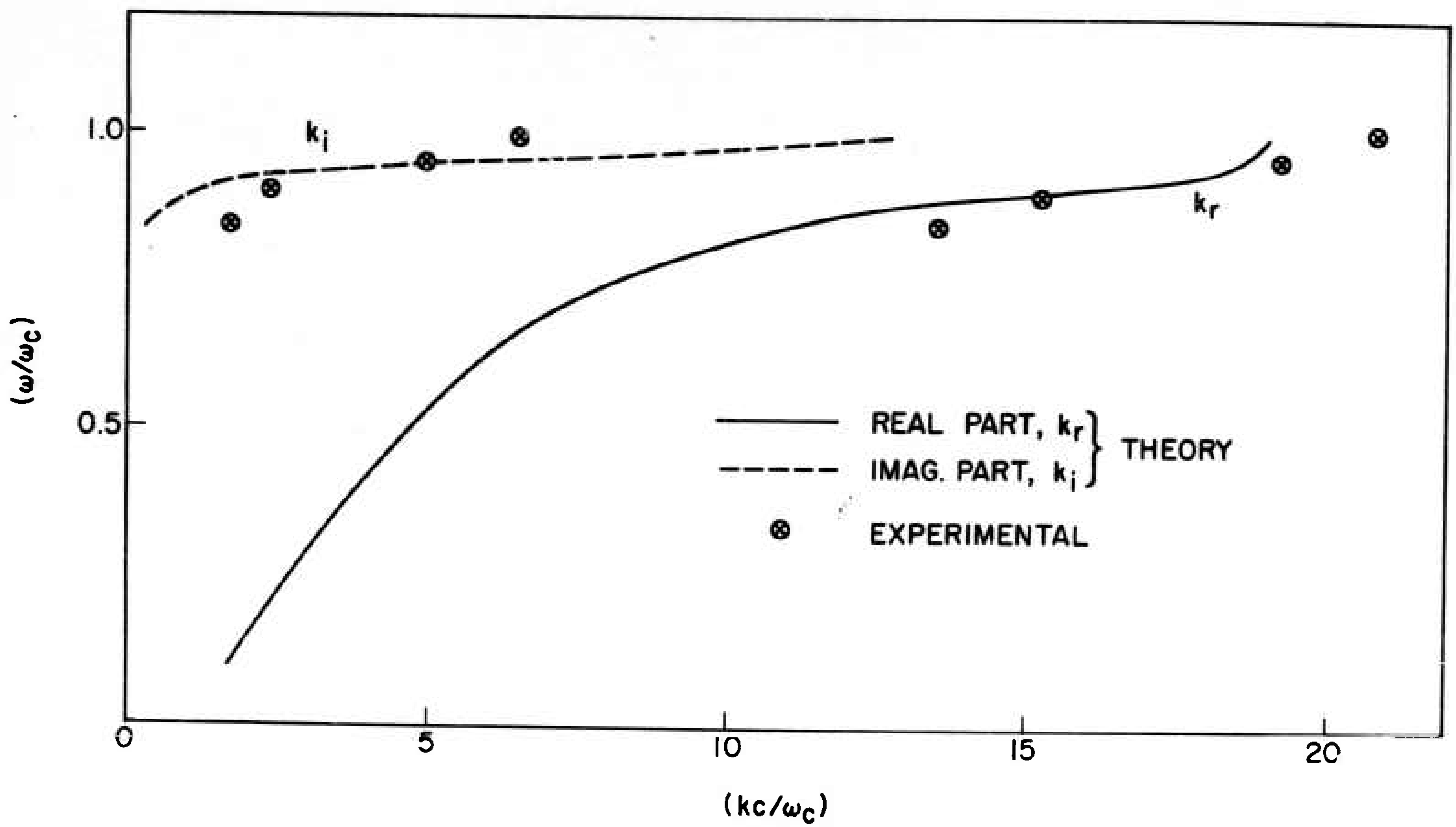
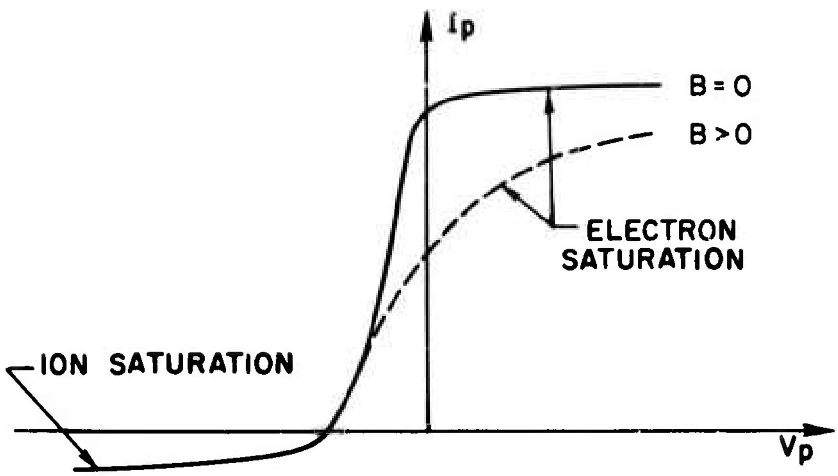


Fig. 9. Whistler dispersion characteristics: Comparison between theory $((\omega_p \omega_c)^2 = 20$, $T_e = 3$ eV, $(\nu/\omega_c) = 0.01$ and experiment $((\omega_p^2/\omega_c^2) = 16.4$, $T_e \approx 3.3$ eV, $f_c = 2$GHz).

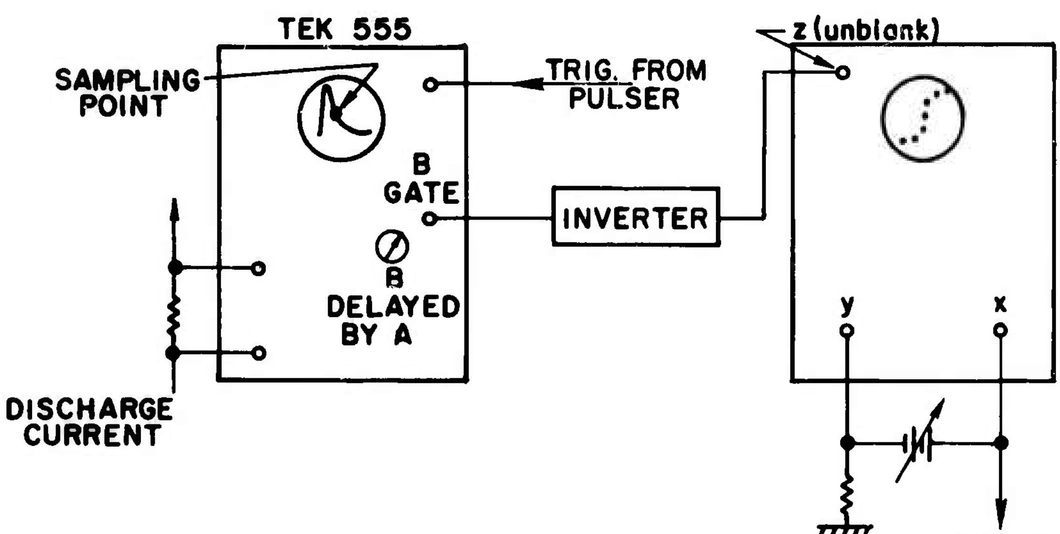
Apart from the foregoing comments on cyclotron and plasma, frequency calibration, which will be considered further during the coming quarter, there is the important question of precise electron temperature measurement during the afterglow, since the damping is extremely sensitive to this quantity. Suitable diagnostic techniques have been under study. For the measurements given in Fig. 9, a pulsed probe method developed by Hosea[7] was used. The theory of this is due to Bohm et al[8], for the zero magnetic field case. It is hoped that by working with only weak magnetic fields, i.e., for which the ion Larmor radii are much larger than the probe dimensions, this theory may be directly applicable to the whistler experiment. Under these conditions, it may be assued that the collection of high energy electrons is unperturbed by the magnetic field. This is not the case, of course, for low energy electrons. With these assumptions a probe characteristic as shown by the dotted curve in Fig. 10(a) should be obtained. By using the lower portion of the curve, it should be possible to determine the electron temperature.

Because the reflex discharge is operated in a pulsed mode, it is necessary to provide a sampling circuit to obtain the probe characteristic curves. The circuit used is shown in Fig. 10(b). The sampling point in the afterglow is determined by setting the time delay on the 'B' time-base. The 'B' gate is then used to unblank an oscilloscope for a period of about 1 μsec. By slowly varying the voltage of the probe power supply, a series of dots is traced on the screen.

A small planar probe was constructed by encapsulating a cylindrical probe in glass, and then grinding a flat face parallel to the axis of the cylinder. Preliminary measurements have indicated electron temperatures which generally seem rather low for an afterglow discharge. It would be highly desirable to have an alternative method of measurement. This question will be pursued during the coming reporting period.



(a) PROBE CHARACTERISTICS



(b) SAMPLING CIRCUIT

Fig. 10. Probe measurements in the afterglow.

V. FUTURE PROGRAM

Most of the details of our program for the coming quarter have been dealt with in the relevant theoretical and experimental subsections of Sections II-IV. Summarizing, the program is as follows:

(i) Beam/plasma amplification with transverse modulation -- Theoretical work will continue on beam/surface wave interactions in the $m = 0$ and $m = 1$ modes, with particular emphasis on the nature of the wave growth, i.e., absolute or convective. Supporting experiments will be carried out in the continuously-pumped system using a hot-cathode electron gun to produce the electron beam and the plasma.

(ii) Electrostatic wave amplification in magnetoplasmas -- Further measurements of the noise spectrum due to magnetoplasma wave excitation by electrons with transverse energy will be made in the magnetic field configuration described in this report, first with a view to identifying the various frequencies so far observed, then with the aim of verifying the theory quantitatively for a delta-function beam interacting with a cold plasma.

(iii) Electromagnetic wave amplification in magnetoplasmas -- The report on our computations of whistler instabilities should be completed during the coming reporting period. The work suggests strongly that competing instabilities will be stronger than whistler mode growth for beam-type electron velocity distributions. Other alternatives, such as the loss-cone distribution, will be examined numerically. Parametric growth will also be studied theoretically and, if time permits, experimentally. The measurements of whistler dispersion will be continued, particularly in the region near the cyclotron frequency where collisionless damping is important.

VI. REFERENCES

1. K. E. Lonngren, IEEE Trans., MTT-14, 494 (1966).

2. D. Kallum, H. Unz and K. E. Lonngren, IEEE Trans., MTT-15, 326 (1967).

3. K. B. Persson, J. App. Phys. 36, 3086 (1965).

4. J. A. Tataronis, Institute for Plasma Research Report No. 205, Stanford University, Stanford, California (December 1967).

5. Hirshfield, J. L., and Wachtel, J. M., Phys. Rev. Letters 12, 533 (1964).

6. Bell, T. F., and Buneman, O., Phys. Rev. 133A, 1300 (1964).

7. J. Hosea, Institute for Plasma Research Report No. 83, Stanford University, Stanford, California (August 1966).

8. D. Bohm, E.H.S. Burhop and H.S.W. Massey, The Characteristics of Electrical Discharges in Magnetic Fields. Ed. A. Guthrie and R. K. Wakerling (McGraw-Hill Book Company, New York 1949), Ch. 2.

PUBLICATIONS, LECTURES, REPORTS AND CONFERENCES

Contract DA-28-043 AMC-03041(E)

1 December 1967 - 29 February 1968

Contract Year I (1966-1967)

1. Crawford, F. W., "Status Review of Microwave Plasma Device Research"
   *IEEE San Francisco Section PGED,
   Stanford, California, March 1966.
   I.P.R. 57 (March 1966).

2. Abraham, E. E., Crawford, F. W., and Mills, D. M., "Beam-Plasma Interaction with Transverse Modulation"
   *Proc. 6th International Conference on Microwave and Optical Frequency Generation and Amplification, Cambridge, England, September 1966 (Institution of Electrical Engineers, London, 1966), Conference Publication No. 27, 470-474.
   *24th Annual Conference on Electron Device Research, Pasadena, June 1966.
   I.P.R. 88 (August 1966).

3. Crawford, F. W., "European Travel Report"
   I.P.R. 116 (October 1966).

4. Diament, P., "Magnetoplasma Wave Properties"
   I.P.R. 119 (February 1967)

Quarterly Status Reports:

No. 1 (1 March - 31 May 1966)
I.P.R. 91 (September 1966).

No. 2 (1 June - 31 August 1966)
I.P.R. 107 (October 1966)

No. 3 (1 September - 30 November 1966)
I.P.R. 127 (December 1966)

No. 4 (1 December 1966 - 28 February 1967)
I.P.R. 144 (May 1967)

Contract Year II (1967-1968)

1. Crawford, F. W., and Tataronis, J. A., "Some Studies of Whistler Mode Amplification"
I.P.R. 151 (April 1967)
*Proc. 8th International Conference on Phenomena in Ionized Gases, Vienna, Austria, August 1967 (Springer Verlag, Vienna, 1967) p. 386.

2. Diament, P., "Inverse Velocity Space Spectra and Kinetic Equations"
I.P.R. 173 (June 1967)
Am. J. Phys. 35, 906-912 (October 1967)

3. Diament, P., "Integral Equations for Inhomogeneous Magnetoplasma Waves"
I.P.R. 174 (June 1967).

4. Self, S. A., "Waves on An Electron Beam in a Vacuum or in a Plasma"
I.P.R. 195 (September 1967)

Quarterly Status Reports:

No. 5 (1 March - 31 May 1967)
I.P.R. 170 (June 1967).

No. 6 (1 June - 31 August 1967)
I.P.R. 201 (September 1967).

No. 7 (1 September - 30 November 1967)
I.P.R. 217 (December 1967).

No. 8 (1 December 1967 - 29 February 1968)
I.P.R. 231 (March 1968)

---

* = Conference presentation

I.P.R. = Institute for Plasma Research Report, Stanford University

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Stanford University Stanford, California	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP NA

3. REPORT TITLE

INVESTIGATION OF FAST WAVE BEAM/PLASMA INTERACTIONS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Eighth Quarterly Report (1 December 1967 - 29 February 1968)

5. AUTHOR(S) *(First name, middle initial, last name)*

STAFF

6. REPORT DATE March 1968	7a. TOTAL NO. OF PAGES 28	7b. NO. OF REFS 8

8a. CONTRACT OR GRANT NO. DA 28-043-AMC-02041(E) b. PROJECT NO. 7900.21.243.40.01.50.410.5 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) SU-IPR 231 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* ECOM-02041-12

10. DISTRIBUTION STATEMENT

This document is subject to special export controls and each transmittal to foreign goverments or foreign nationals may be made only with prior approval of CG, USAECOM, Attn: AMSEL-KL-TM, Ft. Monmouth, N.J. 07703

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY U.S. Army Electronics Command Ft. Monmouth, N. J. - AMSEL-KL-TM

13. ABSTRACT

This report describes a program of work on beam/plasma interaction. Both electrostatic and electromagnetic wave amplifying mechanisms are under investigation. For the former, studies in the absence of a static magnetic field are directed towards verifying the theory for beam/surface wave amplification. Two distinctly different lines are being followed for interactions in the presence of a static magnetic field: Electrostatic cyclotron harmonic wave interaction is being examined, both theoretically and experimentally, and the potentialities of electromagnetic wave growth in the "whistler" mode are being investigated.

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Beam/Plasma						
Fast Wave Interaction						
Plasma Coupling						
Transverse Interaction						
Microwave Amplification						
High Power						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through
_______________________________________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through
_______________________________________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through
_______________________________________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS), (S), (C), or (U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, roles, and weights is optional.